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THE METEOROID HAZARD TO PROJECT APOLLO

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THE METEOROID HAZARD TO PROJECT APOLLO

Abstract

In this report, emphasis is put on the uncertainties in available knowledge. No rational distinction can be made between a severe hazard requiring large weight penalties in spacecraft design and a harmless nuisance. There is sufficient information for the design of critical experiments; it appears that currently conceived satellites would be very useful in reducing the margins of error.

[redacted]

INTRODUCTION

1.0 The solar system is populated with a distribution of masses ranging from the sun itself down to microscopic dust. The hazard to Project Apollo includes any effect on mission success or mission safety owing to collision with these masses.

Enhanced or reduced hazards occur in regions where either the mass or velocity distribution of the particles is affected. For instance, near a body such as the earth, the velocities of the particles are increased. There may be a large number of dust particles in orbits around the earth. On the earth's surface, the shielding of the atmosphere reduces the hazard to nil. On the moon's surface, it seems likely that quantities of secondary particles (of low velocity) will be generated by each primary impact. The flux of particles is thereby greatly increased.

The hazard to a given space flight may be described by two numbers: firstly, a puncture probability from larger and less frequent masses; and secondly, a rate of surface erosion from the impact of fine dust particles.

Both numbers are proportional to the "exposure", E, of the spacecraft, defined as the product of its area by the time it spends in a region of homogeneous danger. The units of exposure are chosen as square meters seconds.

The total hazard to a mission is then a sum of hazard rates (per unit exposure) in the various regions, times the exposures in those regions.

Optimum information for Apollo would come from penetration depths measured on recovered capsules. For statistical significance, it is desirable that the total exposure be at least ten times the Apollo exposure*. All recovered surfaces (as Mercury and Discoverer) should be thoroughly analyzed, regardless of exposure.

The currently available data is largely in the form of (a) particle fluxes (known most accurately in terms of -- for instance -- momentum or trail brightness), and (b) penetrations measured for laboratory particles at velocities an order of magnitude slower than meteoric velocities.

In the following pages some of the known data will be reviewed. Emphasis will be placed on the uncertainties.

* For the purposes of this review, we assume the Apollo area to be 70 m^2, and the length of the mission to be ten days. The exposure is about 6×10^7 m^2 sec.

Data on regions other than the near earth are very sparse and must be supplemented with speculation*.

2.0 Meteoroids: General

The meteoroids appear to be members of the solar system. As such, their velocities (at the earth's surface) range from about 10 to 70 km/sec, depending on their orbits. They fall into several families characterized by density and by size.

The first group is related to the asteroids. The density ranges from 3 (stone) to 7 (iron). These are observed as recovered "meteorites" and form the mass of visual meteors brighter than magnitude -3.

The second group appears to be cometary debris. Often localized in the orbit of a known comet, these particles are of very low density (.05 grams/cc) and are described as "dust balls". These are the fainter visual meteors and the radar meteors.

"Micrometeoroids" are defined as particles sufficiently small that the heat generated in passing through the atmosphere can be radiated away without melting.

Going to smaller sizes, there is expected to be a cut-off around a micron in radius, caused by solar radiation pressure and other effects. Most of this "dust" is expected to be compact in structure.

2.1 Spatial Distribution

The spatial distribution of meteors is not uniform. The occurrence of meteor showers may raise the flux of visible meteors from a few times to several orders of magnitude. The change in the micrometeoroid population is probably comparable. The showers are associated with the orbits of comets, and repeat yearly as the earth passes through the swarm. Intense showers may have the (longer) period of the parent comet. Several prominent showers are tabulated in Appendix I, which is taken from Duberg (1962).

3.0 Flux

It is customary to represent experimental data on the flux of meteoroids by plotting the cumulative flux (i.e.

* Certain references which have been useful throughout this study appear in the bibliography under "general references". In particular, Duberg (1962) was invaluable.

the number of meteoroids of mass greater than m) against the mass, m. The populations approximate straight lines on log paper. Such a distribution can be analytically represented as follows:

$$N=N_o\ (m/m_o)^{-s}. \qquad (1)$$

N is the flux in meters^{-2} seconds^{-1}, m is the mass in kilograms. ($N_o m_o^s$) is a constant broken into two parts for dimensional reasons, and s is the "population index". Depending on the physical processes which produce the distribution, s may be a function of mass. Processes decreasing the number of small particles result in small values of s, and vice versa.

3.1 Information for the Near-Earth Cumulative Flux Chart

Log cumulative flux, N ($m^{-2}sec^{-1}$) is plotted against log mass, m (kg) in figure 1. The hatching indicates fluxes for which experimental data exists. The breadth of the band corresponds to the uncertainty. The expected number of impacts of masses greater than m on a mission of exposure E is E x N.

The horizontal line at a flux of $2x10^{-8}m^{-2}sec^{-1}$ is the reciprocal exposure of Apollo. At this flux level there is a 50% probability of one impact per mission. Note that no data exists for the flux levels corresponding to probable numbers of impacts from 1/10 to 10^3 per mission.

The kind of information available may be indicated by an example. The flux corresponding to one impact per thousand Apollo missions is $2x10^{-11}m^{-2}sec^{-1}$. This meteoroid, entering the earth's atmosphere, would give rise to a meteor detectable by radar of about the tenth visible magnitude. From figure 1, the mass could be from 10^{-4} to 10^{-7} kg. It would be hypothesized a "dust ball" of density .05 grams/cc, and would have a radius between a millimeter and a centimeter. The sources for figure 1 are briefly discussed below. Pertinent numerical values used in constructing the graph are shown in Appendix II.

3.1.1 Flux of Meteorites (Harrison Brown, 1960)

The number of observed and recovered meteorite falls are tabulated for three very densely populated areas of the earth covering 100 years. The mass range is 1 to $5x10^3$ kg.

Uncertainties:-- His collection area is uncertain, and has been corrected upwards a factor of three. Collection

efficiency is poor for daylight falls and for masses less than 10 kg. Estimated corrections are made for these as well. These may be the best data in the entire chart from a critical standpoint.

3.1.2 Flux of Meteors (F.L. Whipple, 1958 and 1961)

Whipple's estimates represent the entire mass of available data. The fixed points he chooses (1961) are as follows: s=1.186; the flux of meteors brighter than magnitude 5.5, 200 million per earth day; the mass of a meteor of magnitude 5.5, 0.16 grams. (25 g for a zero magnitude meteor) Whipple feels that he has adopted a large value for this mass as a safety factor for engineering purposes.

Uncertainties:-- The relation between the mass and luminosity of a meteor involves considerable computation on rather tenuous assumptions. Thus the range of masses estimated for a zero magnitude meteor is from 25 grams (Whipple) to 0.25 grams (Watson, 1956). Ablated atoms from the surface of the meteorite collide with air atoms; ionization takes place, and during recombination, some visual light is emitted. The estimation of the "luminous efficiency" of this process is the important question*. It is fairly sure that for meteoroids of given density, the luminosity is proportional to mass. Hence a one-point calibration would increase the usefulness of a vast quantity of information. Experiments aimed at producing artificial meteors of known mass have been proposed, and should be encouraged.

3.1.3 Flux of Asteroids, Fireballs, and Meteors (Hawkins, 1959)

The mass distribution of asteroids can be fitted onto that plotted here with only modest imagination.

The fireballs (brilliant meteors, visual magnitudes -3 to -10) have been quantitatively observed for many years by visual observers.

Uncertainties:-- The scanning area of such an observer is difficult to estimate and will vary systematically with meteor brightness; corrections are applied. Hawkins prefers to set the fireball flux equal to the (photographic) meteor flux at magnitude -3; s=-1 for the fireballs. The fainter meteors are assumed to be "dust balls".

3.1.4 The Harvard Meteor Program (Hawkins and Upton, 1958)

Stereoscopic photographs of the sky (~30-mile baseline) give very precise data on the magnitude and velocity of

* Several chapters in Opik (1958) are devoted to this problem.

meteors within the limitations of emulsion sensitivity. The plot in figure 1 is based on over a year's sampling, about 250 meteors.

Uncertainties:-- This (and similar) programs give the only excellent data on meteor vector velocity. The computation of mass is no better off than indicated above, except that the detailed brightness variation along the path can be taken into account.

3.1.5 Radar Meteors

Meteors to the 15th magnitude can be detected by radar. Unfortunately, quantitative information on fluxes below the visual range is fraught with systematic errors associated with the loss of high, faint meteors. The conversion from radar magnitude (i.e. scattering power) to mass is no better than that for photographic meteors. Velocity information is available, at least for some meteors, with a precision about 10x worse than the photographic precision. The population index indicated from the data for the range to the fifteenth magnitude (3×10^{-8} kg on Hawkins' scale) is s=1; after correction for systematic error, this might range up to 1.5.

3.1.6 Direct (Satellite) Measurements (McCracken & Alexander, 1961)

A number of satellite and sounding rocket measurements form a self-consistent set of data obtained in the form of "impulses" detected by microphones. The magnitudes of the impulses are proportional to momentum according to calibrations made with low speed particles.

Instance:-- Explorer - ×4",
for 40 days n
Ex t

Un -- Unless some major systematic error is ac measurements are quite good. The momentum calibration is probably uncertain within a factor of three. In the conversion to mass data, the velocity uncertainty adds another factor of 2. The Russians feel that their microphone systems are energy-sensitive, since the momentum carried away by ejecta from an impact crater exceeds the incident momentum; the volume of ejecta is proportional to incident energy. One would like to see a quantitative discussion of this point of view.

3.1.7 Micrometeoroids: Zodiacal Light (see Dubin and McCracken, 1961, for a summary)

The zodiacal light is explained as in part the result of scattering by dust particles. The resulting densities

of interplanetary dust are very small (10^{-3}) relative to those indicated by the direct measurements (section 3.1.6) which cover the same mass range.

3.1.8 Dust (Hemenway and Soberman, 1962)

Dust is collected in a recoverable sounding rocket (The "Venus Fly Trap") at an altitude of 100 km. The dust is sized and counted with an electron microscope. The dust is incident with surprisingly small velocities and sizes (submicron) and in large numbers, suggesting the break-up of fluffy particles. Flux versus diameter is tabulated. The data are good; their application to meteoroid fluxes outside the earth's atmosphere is uncertain.

4.0 Penetration

To supplement the flux-mass plot, we now attempt to construct a plot of mean penetration versus the mass of particle incident at meteoric speeds, i.e. from 10 to 70 km per second. There is little experimental information on impacts at velocities above 10 km/sec. Unfortunately, since the velocity of sound is about 5 km/sec in most metals, the impact process is changing from a subsonic to a hypersonic character, and the data cannot be usefully extrapolated. Some insight may be gained from explosions dissipating energies comparable with high speed impact. If the explosive is not deeply buried, the situation immediately after ignition is not vastly different.

The indications are: that the hypersonic impact craters are hemispherical; and that the total ejected mass, M_e, is nearly proportional to the incident kinetic energy. A power of the velocity somewhat less than the square is likely. We assume:

$$M_e = \frac{1}{2K} mv^2 \qquad (2)$$

where m is the incident mass, v the velocity, and K a constant.
M.K.S. units are used.

K has the dimensions of velocity squared. The values suggested by various investigators will be summarized in Appendix III.

4.1 Data Sources

4.1.1 Whipple (1958)

Whipple (F.L.) estimated crater volume by equating the incident kinetic energy to the heat required to melt the

target material (Specific heat plus latent heat must be used.), we obtain $K=1.05\times10^6$ joules/kg ($K^{1/2}$= 1.0 km/sec). This number is not particularly different for steel.

4.1.2 A curve given by Gault, Shoemaker, and Moore (1962) for cratering in basalt, earth, and so on, including explosion craters as well as impact craters, indicates a value of K of 1.1×10^5 joules/kg. This should be an upper limit for estimates of cratering in metals.

4.1.3 Other estimates of this type plotted in Duberg (1962) and Davison (1961) give estimates of K bracketed by these.

4.2 Selected Values

The estimates are in good order of magnitude agreement. Other estimates can be very much higher or lower in the meteoric velocity range. It is reasonable to weight the results equally, indicating the spread of the estimates as a broad line on figure 2. An additional uncertainty arises from the velocity range. For the construction of figure 2, we assume that the crater is hemispherical of radius R_e, and that the target material has a density ρ_e.

$$R_e = \left(\frac{3}{4\pi K \rho_e} mv^2 \right)^{1/3} \qquad (3)$$

Equation three is plotted. The slow variation of R_e with incident mass should be noted. In interpreting figure 2, it must be remembered that for thin material, the penetration will be 1.5x or so that in a semi-infinite slab.

Before leaving this section, we should make a few remarks about the behavior of this penetration criterion.

Observing equation 2, it should be noted that the ratio of ejected to incident mass depends only on the ratio of v^2 to K.

$$\frac{M_e}{m} = \frac{v^2}{2K} \qquad (4)$$

$K^{1/2}$ is about .5 km/sec. Hence in order of magnitude, for v of one kilometer per second, the mass ratio is about 2, and for 10 km/sec, about 200.

For a spherical meteoroid of radius r and density ρ, we obtain

$$\frac{R_e}{r} = \left(\frac{\rho}{\rho_e} \frac{v^2}{K} \right)^{1/3} \qquad (5)$$

i.e., only the ratio of the radii depends on the density of the incident particle. This must surely fail for the dust balls, which would have bigger radii than the predicted crater in the lower velocity ranges.

5.0 Penetration Flux - Probability - Near-Earth

The penetration flux or probability curve may now be constructed from figures 1 and 2. It shows the cumulative number of craters of size greater than R as a function of R, per square meter second.

An auxiliary scale is calibrated in probable number of hits per Apollo mission.

The upper limit indicates clearly that 1 centimeter dents (punctures of 1.5 cm solid skins) would be expected (50% probability) for an Apollo mission, and that probability is 10^{-3} for a 6 cm dent (puncture of a 10 cm solid skin), at least in near-earth orbit.

These hazards may be reduced perhaps by 1/2, if the particles are dust balls. Multiple skin "meteor bumpers" may reduce the maximum hazard by 1/3.

Even then, for .999 chance of no puncture, a bumper equivalent to 1.6 cm of metal is required!

5.1 Penetration Flux on the Lunar Surface (Gault, Shoemaker and Moore, 1962)

The preliminary results of Gault, Shoemaker and Moore indicate that for each incident meteoroid, at least 10^4 secondaries will be ejected. Equation (4) above showed that at low velocity (10 km/sec) a meteoroid might eject 100x the incident mass. Obviously this will be principally in small fragments.

If the penetration law of (2) is valid, no significant effect on the penetration rate will occur; the total kinetic energy available to the secondaries is less than that incident, and the net ejection of mass from surface will be only doubled by the secondary flux. An estimate of the secondary velocity can be made. The total secondary kinetic energy is less than that incident:

$$1/2 \sum_1 m_i \, v_i^2 < 1/2 \, MV^2 \qquad (6)$$

From equation (2), the total mass ejected is proportional to the incident kinetic energy:

$$M_e = \sum_1 m_i = \frac{1}{2K} MV^2 \qquad (7)$$

Then

$$\frac{\sum_1 m_i \, v_i^2}{\sum m_i} < 2K \sim (1.4 \text{ km/sec})^2, \qquad (8)$$

independent of primary mass or velocity. Of course, a few particles may have very high velocities. Equation (8)

indicates low speed collisions, and probably few tertiary particles.

Aside from the Apollo vehicle, the astronauts themselves will be exposed to the meteoroid flux on the lunar surface. Their exposure may be estimated as 2 square meters for one day, or about $1.7 \times 10^{5} m^{-2} sec^{-1}$.

Figure 3 implies that a penetration of as much as 2 mm of aluminum might be expected, with a probability of 10^{-3} for an 2 cm puncture.

Particularly considering the unknown, low velocity, secondary flux, it would be desirable to expose space suit materials on the lunar surface. It should be relatively easy to achieve this with a Surveyor Lander experiment.

6.0 Erosive Flux

It is not certain from the data that an erosion problem exists. In figure 4, the cumulative number of pits of radius greater than R times pit area is plotted against R.

At the worst, the "Venus Fly Trap" data (section 3.1.8) contributes a twofold coverage of Apollo with 60 micron radius pits, or a net erosion of about 100 microns in the ten-day mission.

Minor changes in flux or penetration assumptions could reduce this coverage to 10^{-2} of Apollo. If a major erosion problem exists, it can easily be measured on any recoverable capsule with a two-week flight time.

7.0 Conclusions from Available Information

Our conclusions are, in brief, that there is sufficient information for the design of good critical experiments, but that there is not enough information to allow sensible engineering design of Apollo.

An experimental design will be aimed at a known flux, corresponding to some number of impacts on the Apollo mission. The exposure necessary for the experiment is determined, and the data is adequate to allow design of sensors.

Conversely, if Apollo is to be designed from the kind of information available here, then, using figure 3, we see that for 10^{-3} probability, the expected penetration could range from .1 to 10cm thickness in aluminum. Assuming

an Apollo area of 70 square meters, the difference in these estimates corresponds to16000 kg, a substantial portion of the Apollo weight.

This figure may be considerably reduced. If meteor bumpers are successfully proven, a 3x reduction is plausible, giving a figure of 5000 kg. This uncertainty (5-1/2 tons) is a costly hindrance to spacecraft design.

It should be emphasized that these estimates rest on the guesswork of many workers. Some of these guesses are grossly wrong. One cannot guarantee that the true hazard lies even within the range described.

It is very desirable that experiments specifically designed to measure meteoroid damage to exposures comparable with Apollo be performed as soon as possible. The results might be either to set more stringent conditions on the protective skin, or to release several tons of structural weight, increasing the margins for mission capability. Several experiments are briefly described below.

8.0 Proposed Measurements

Several varieties of measurements offering improvement of our knowledge of the meteoroid hazard are covered.

8.1 S55

The principal sensors of the S55 comprise 160 pressurized cells (area 3 m^2) with 1 to 5 mil wall thicknesses (2.5 to 13×10^{-5}m). If the satellite operates for 1 year, its exposure will be $8.5 \times 10^7 m^2$ sec, about an Apollo exposure.

From figure 3, the total number of punctures of 10^{-4}m material might range from 3 to 10^{10}. The rate of failure of the pressure cells can hardly help but reduce the uncertainty very markedly.

8.2 S65

The proposed S65 has a sensitive area of 14 m^2 of 15 mil aluminum sheet (4×10^{-4}m), using a condenser-type detector. In a year, its exposure would be seven times that of Apollo. The information from either S55 or S65 will not bear directly on the .999 penetration hazard for Apollo which arises from fluxes 6 orders of magnitude smaller and penetrations 100x deeper. However, the great reduction in uncertainty at the higher flux level would allow more intelligent estimates of the penetration hazard.

8.3 Saturn Apollo R&D Flights

The flight of Saturn Apollo R&D missions could in principal give information about fluxes in the mass range pertinent to Apollo. Since the Apollo area is only 5 times that of S65, significant information still involves a long time, perhaps two months instead of a year for S65, even if particles of the same mass are measured.

8.4 Other Possibilities - Satellite

The only plausible, direct experiments of exposures greatly exceeding Apollo would be based on balloons, such as Echo. One hundred feet in diameter, Echo accumulates 4 Apollo exposures in one day, 1500 in a year. Some thought should be given to light weight instruments which could be contained within the balloon and give some measure of the penetration. To be useful, an indication of the individual area of larger holes would be necessary. Certainly, the integrated illumination of the interior could be measured. If the balloon can be persuaded to rotate and precess, one could devise a camera obscura, as suggested by B. T. Howard and D. B. James, in which the sensor is directly illuminated by the sun through the holes. This scheme would give hole areas. Calibration in terms of Apollo penetration would still be necessary.

8.5 Other possibilities - Ground Based Experiments

As indicated above, the particles associated with the one in one thousand impact are radar meteors of approximately the tenth visual magnitude. No possibility of improving the calibration or utilization of presently available ground-based data should be overlooked.

8.6 Lunar Surface

The problem of measurement of the lunar surface flux has not been touched. Currently, four pounds are allocated to a micrometeoroid detector on a Surveyor Lander. The secondary flux is expected to be so high that a detector of relatively small exposure might suffice. Considering the low velocities, the calibration of a momentum-type detector would be in some question. We would suggest that either a penetration or energy-sensing detector would be preferable. A penetration measurement directly applicable to space suit design would be of great importance.

8.7 Impact Measurements

High velocity impact studies are currently underway. Figure 1 suggests that the range of masses offering

penetration hazards to Apollo (i.e. corresponding to from 1 to 10^{-3} impacts per mission) is at most from 5×10^{-5} to 10^{-10} kg. In compact particles, this corresponds to diameters from a few millimeters to thirty microns. The impact of such particles is of primary interest, if the velocities can be brought to appropriate values. 20 km/sec would be a great help.

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APPENDIX I

Meteor Showers and Mean Velocities

Dates	Name	Velocity km/sec
Jan. 3	Quadrantids *	44.1
Feb.		
Mar.		
April 21	Lyrids	48.6
May 4 – 6	Eta Aquarides	60
29 – June 19	Arietids *	37
24 – July 25	Beta Taurids *	31
28	Delta Aquarides	43
Aug. 1 – 14	Perseids	60.5
Sept.		
Oct. 10	Draconids	37
20 – 23	Orionids	66.5
Nov. 3 – 10	Taurids	37
16 – 17	Leonids	72
23 – Dec. 6	Andromedes	16
12 – 13	Geminids	36.4
22	Ursids	37

*Daytime Shower

APPENDIX II

NUMERICAL VALUES FOR FLUX CHART

Sect.	Reference	s	Range(kg)	Raw Data (?)	$N_o(m^{-2}sec^{-1})$	m (kg)	Exposure(m^2sec)
3.1.1	Brown (1961)	0.76	$1\text{-}5\ 10^3$	Between 1360 and 4100 falls per earth year	2×10^{-19}	1 kg	$1.6\ 10^{21}\ m^2$sec
	Addendum			X 3.4			
3.1.2	Whipple (1961)	1.186	10^{-12} to 10^{-3}	$200x10^6$ per earth day bright than mag. 5.5=0.16 gram	$4.5x10^{-12}$	$1.6x10^{-4}$	Not Applicable
3.1.3	Hawkins (1959) Fireballs	1.0	$6x10^{-2}$ to 40	Flux equal to (3.14) component at magnitude -3 (.22 kg)			10^{19} (estimated)
3.1.4	Hawkins & Upton (1958) (Harvard Meteor Project)	1.34	$2x10^{-3}$ to 10^{-1}	log N=-1.34 log m -2.64 N $(km^2hr)^{-1}$, m (gm)	$6x10^{-17}$	1	$3x10^{17}$
3.1.6	McCracken & Alexander (1961) (Explorer VIII)	1.7	10^{-12} 10^{-11} 10^{-10}	Flux, $2.5\ 10^{-2}$ $6\ 10^{-4}$ 0 zero $< 10^{-5}$			$7x10^4$
3.1.7	Soberman & Hemenway (1962)	0.43	.1-3 micron $3x10^{-18}$--10^{-13}g	Census of collected particles versus diameter	$3x10^2$	$8x10^{-14}$	31.meters^{2}sec

APPENDIX III

Data for Penetration Chart

1. Whipple type of estimate $K = C_v(T_f - T_o) + L$

   C_v is the specific heat per unit mass, L the latent heat of fusion, T_f the fusion temperature, T_o the initial temperature (assumed 0°C).

	Aluminum	Iron
T_f °C	659.7	1535
C_v joules/kg°	10^3	5×10^2
L_v joules/kg	3.9×10^5	1.2×10^5
K joules/kg	1.05×10^6	$.89\times10^6$

2. Gault, Shoemaker, and Moore. From their plot of ejected mass as a function of incident energy, we take a set point of 10g ejected for 10^{10} ergs.

   $$K = 10^5 \text{ joules/kg}$$

   This value (ejecta from rock) is expected to be an upper limit.

3. From Duberg (1962), figure 11. The ratio of penetration to particle diameter is plotted. We use equation (5) to obtain the following results. Whipple (1958) computed penetration on the basis of a conical rather than a hemispherical cavity, obtaining larger penetration values. For comparison, we include his "effective K".

	R_e/d at 10 km/sec	K joules/kg
Whipple (1958)	4.3	1.6×10^5 (effective)
Charters & Locke	3.5	2.9×10^5

4. Display:

   In equation 3, $R_e = \left(\frac{3\ v^2}{4\ \pi\ K \rho_e}\right)^{1/3} m^{1/3}$, we use the density of aluminum, 2.7×10^3 kg/m^3, $K=10^6$, and $v=10^4$m/sec to determine the lower limit. For the upper limit, $K=10^5$ and $v=7\times10^4$m/sec are used.

   Lower limit: $R_e = .21\ m^{1/3}$

   Upper limit: $R_e = 1.64\ m^{1/3}$

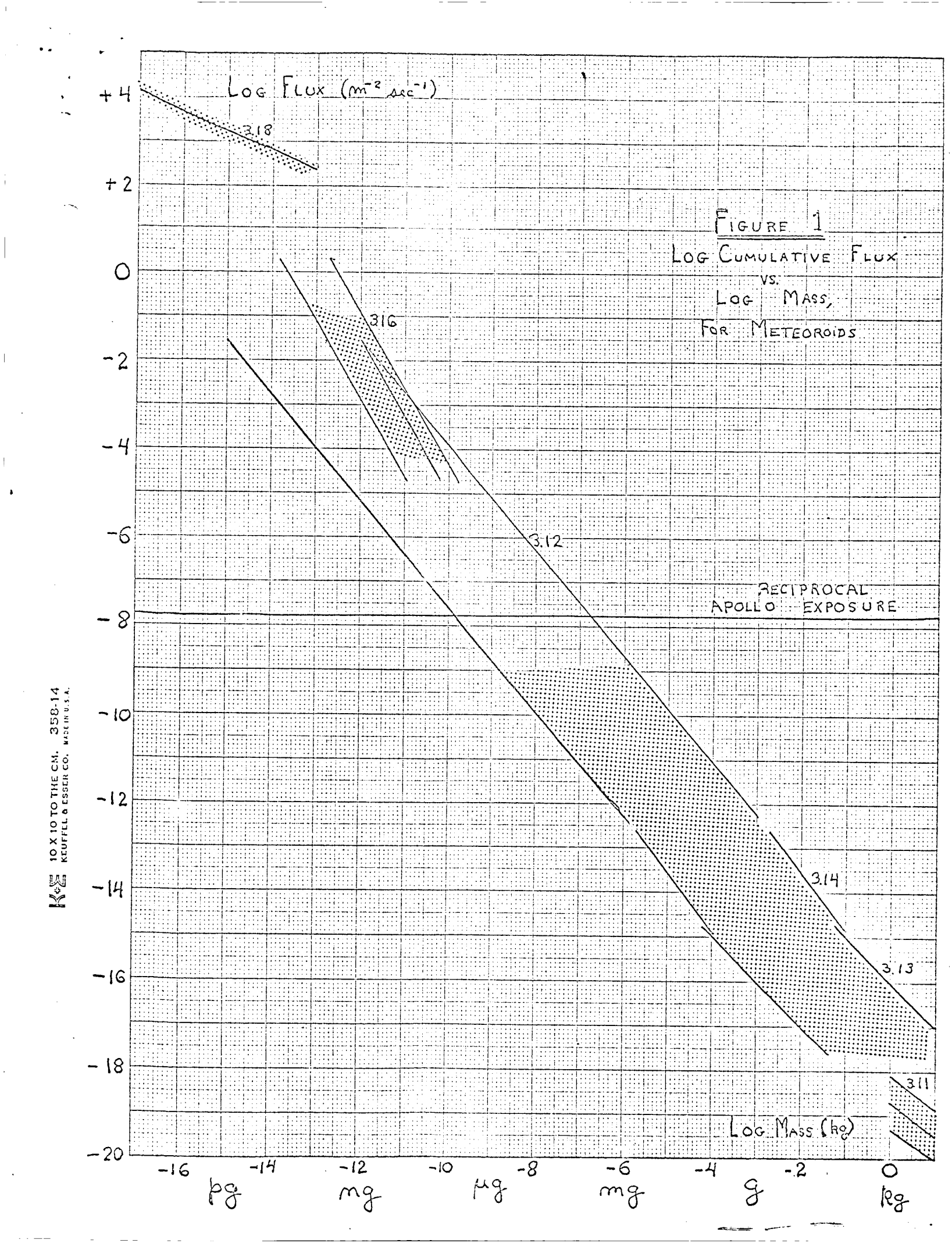
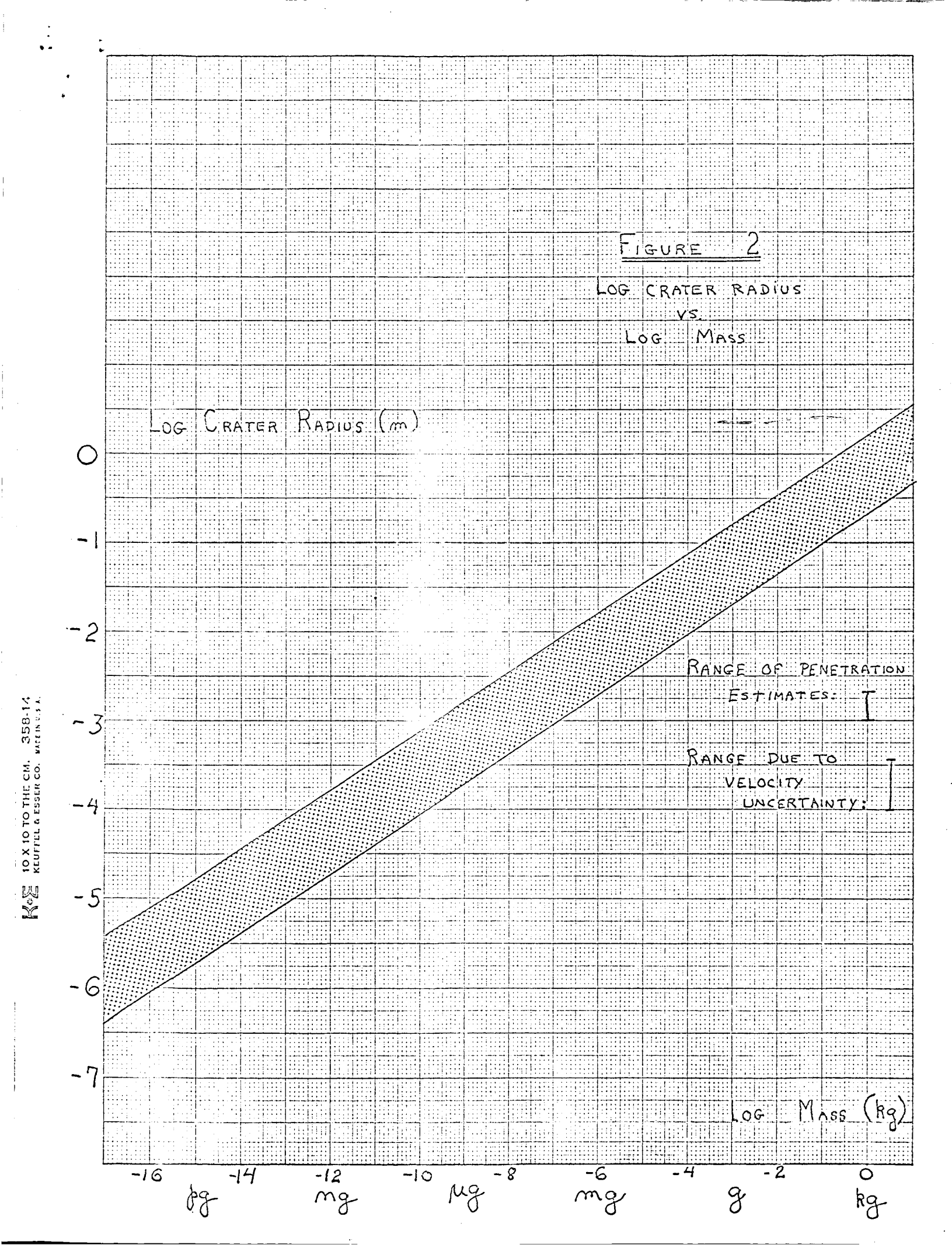


Figure 1
Log Cumulative Flux
vs.
Log Mass,
For Meteoroids

10 X 10 TO THE CM. 358-14
KEUFFEL & ESSER CO. MADE IN U.S.A.



10 X 10 TO THE CM. 358-14
KEUFFEL & ESSER CO. MADE IN U.S.A.

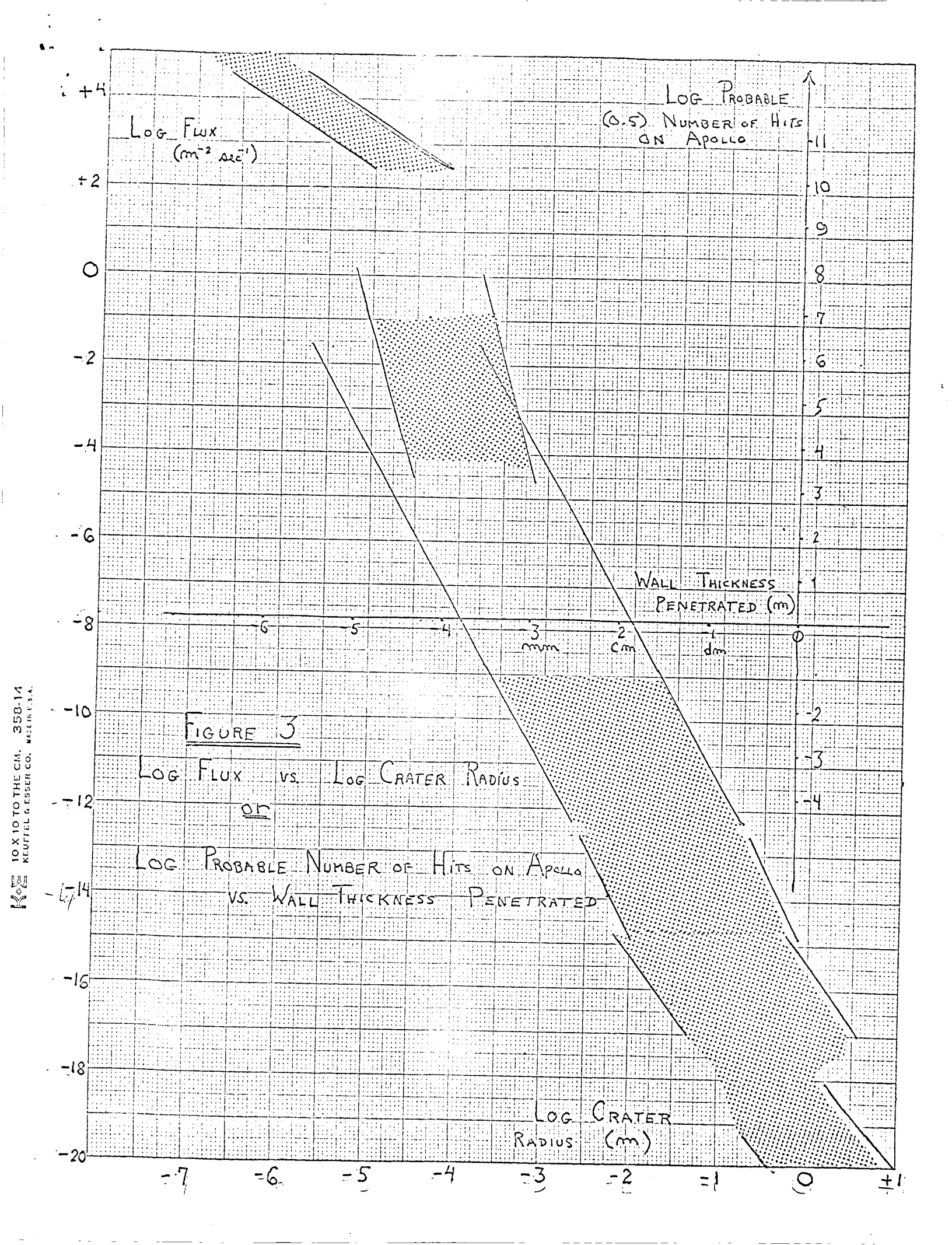


FIGURE 3

LOG FLUX VS. LOG CRATER RADIUS

OR

LOG PROBABLE NUMBER OF HITS ON APOLLO

VS. WALL THICKNESS PENETRATED

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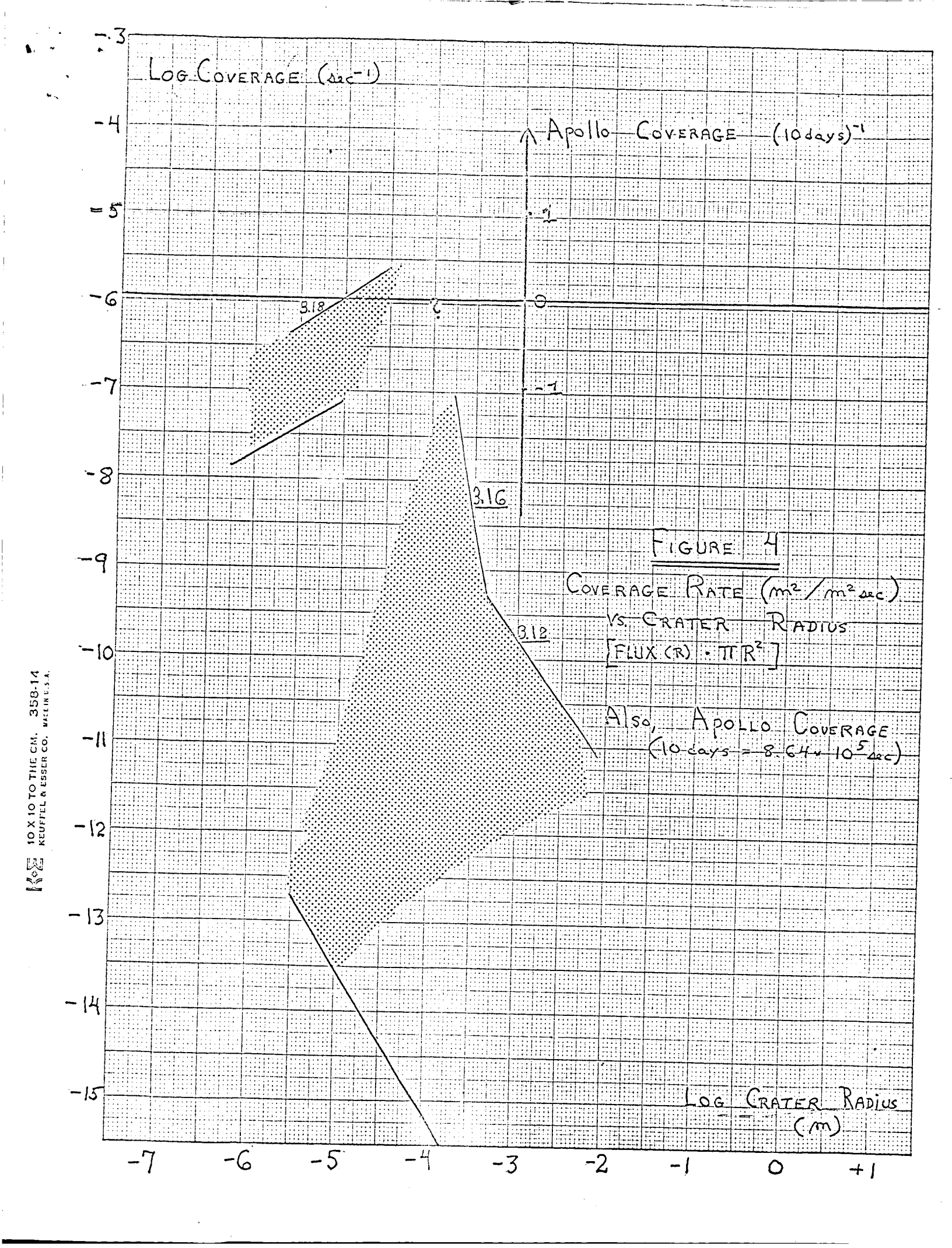

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